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FEEDING TIMES IN (HI, xnγ) REACTIONS

J. O. Newton, F. S. Stephens, and R. M. Diamond

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NUCLEAR REACTIONS $^{150}Sm(^{20}Ne,4n)^{166}Hf$, E = 93 MeV, $^{152,154}Sm(^{20}Ne,4n)^{168,170}Hf$, E = 86 MeV, $^{154}Sm(^{28}Si,4n)^{178}Os$, E = 104 MeV; measured E_{γ}, I_{γ}, recoil-distance Doppler shift. $^{166,168,170}Hf$, ^{178}Os deduced levels and feeding time. Enriched targets.

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J. O. Newton†, F. S. Stephens, and R. M. Diamond

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Abstract

Feeding times, T_f, for population of the quasi-rotational bands in a number of doubly-even nuclei formed in (HI,xn) reactions have been measured with the recoil-distance Doppler-shift technique. Values of 11 ± 3, 5 ± 2.5, 3 ± 3 and $12^{+2.5}_{-4}$ ps were obtained for T_f in the ^{166,168,170}Hf and ^{178}Os nuclei populated by the ^{150,152,154}Sm(^{20}Ne,4n) and ^{154}Sm(^{28}Si,4n) reactions, respectively. In all cases the fraction of slow-feeding component was less than a few percent.

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†Present address: Department of Nuclear Physics, The Australian National University, Canberra, Australia.

1. Introduction

Spectroscopy of the γ-rays following heavy-ion (HI),xn reactions has been a prolific source of information on high-spin states in nuclei. The way in which these states are populated following formation of the highly excited product nucleus, and the nature of the states through which the γ-ray population passes are topics of considerable current interest. A simple model[1]) proposed to explain the experimental data in doubly-even nuclei is illustrated in fig. 1. The highly excited states, formed after neutron emission, first decay by fast E1 transitions down to the region of the yrast line, after which decay must proceed along the yrast region. If, as proposed[1]), this decay occurs among rotational states based mainly on two quasi-particle states, it should be predominantly by E2 transitions. There should be few, if any, traps giving rise to isometric states in the yrast region; thus decay should be fast ($\sim$ few ps). When the population reaches the point where the ground-state band (gsb) intersects the yrast region, it then flows into the gsb. To be in accordance with the previous results[2]) on the feeding times of three nuclei populated by (^{40}Ar,4n) reactions, the transition time from the yrast region to the gsb must also be of the order of picoseconds, as it was found that the mean feeding times, T_f, for the nuclei ^{160}Er, ^{158}Er and ^{156}Er were (6 ± 3) ps, (11 ± 3) ps and (16 ± 3) ps, respectively. These nuclei range from being rotational (^{160}Er) to near vibrational (^{156}Er), and the tendency for the feeding times to become longer as the nuclei become more vibrational is interesting. In all cases the fraction of slow feeding, f_ℓ, was found not to exceed a few percent of the fast ($\sim$ 10 ps) feeding. In order to see whether these results might be of general validity, we have made similar measurements on four more doubly-even nuclei.

2. Experimental Method

The recoil-distance Doppler-shift method was used for these measurements. In this method the excited nuclei recoiling from the target are stopped in a moveable plunger placed near to it. For lifetimes longer than a few picoseconds, the nuclei which decay in the plunger yield an unshifted γ-ray line, while those which decay in flight produce a Doppler-shifted and slightly broadened line when observed in a detector placed at 0° to the beam direction. The broadening arises from the spread in observation angle of the detector and from the spread in recoil velocity due to finite target thickness and to emission of neutrons from the compound system. Only the first two effects are significant in this case. By varying the distance between the target and plunger one can change the fraction, f, of the γ-ray profile which is unshifted. The lifetime can then be deduced from the variation of f as a function of distance, and a knowledge of the velocity of the recoiling nucleus.

The reactions were initiated by beams of ^{20}Ne and ^{28}Si ions from the Berkeley HILAC. Targets were self-supporting metal foils stretched tightly over a holder assembly. The recoiling nuclei from the (HI,4n) reactions were stopped in a lead-covered plunger, whose position could be adjusted to an accuracy of $\pm$ 0.003 mm with a precision micrometer. The target and plunger appeared to be flat and parallel to an accuracy of $\pm$ 0.01 mm when observed by a microscope, except for the 0.5 mg/cm^2 targets. "Unshifted" spectra were obtained by bombarding similar targets evaporated onto 0.0025 cm thick lead foil. Lead foil of the same thickness was attached to the back of the plunger during the recoil-distance measurements so that the γ-ray attenuation was always the same. The γ-rays were detected at 0° to the beam direction in a 6 cm^2 by 1.3 cm thick planar Ge(Li) detector with a resolution of 2 keV (FWHM) at 1 MeV.

Ideally the target thickness should be so chosen that the shifted and unshifted peaks can be completely resolved, but not so thin that background radiation from the plunger, collimators or surface impurities becomes serious. For the $^{150,152,154}Sm(^{20}Ne,4n)$ reactions the optimum target thickness is about 0.5 mg/cm^2 while for the $^{154}Sm(^{28}Si,4n)$ reaction, where the recoiling nuclei have higher energy, it is about 1 mg/cm^2. We were able to make excellent flat targets with 1 mg/cm^2 foils, but the 0.5 mg/cm^2 foils lacked sufficient strength to be stretched tightly. In the case of ^{150}Sm, we succeeded in making a satisfactory target of 0.7 mg/cm^2 thickness, but for the other $(^{20}Ne,4n)$ reactions we used both 1 mg/cm^2 and 0.5 mg/cm^2 foils. This was necessary because our purpose was to determine both the principal feeding time, which is rather short, and also the fraction of population with long feeding times. The former requires that the target be flat so that the plunger can come very close to it, while the latter requires that the shifted and unshifted peaks be completely resolved. Although the mean energy loss of the recoiling Hf nuclei[3]) in a 1 mg/cm^2 samarium foil should only be a little more than half of their initial energy, the straggling appears to be very large and some of them lose all of their energy. At present there is no adequate theory to calculate this effect, but the very sparse experimental data[4,5]) indicate that the straggling is indeed large. This is illustrated in fig. 2 which shows the experimental line shapes for the $10^+ \rightarrow 8^+$ rotational transition in ^{168}Hf with 1 and 0.5 mg/cm^2 targets. Observations of this type might offer a good method of measuring the straggling of very heavy ions.

The mean velocities of the recoiling nuclei were determined from the fractional energy shifts of the completely shifted peaks, obtained by moving the plunger sufficiently far back so that a negligible number of nuclei decayed in it. In determining the centroid of the shifted peak, any counts which occurred in the region of the unshifted peak were ignored. The velocities so obtained, after correction for the finite angular spread of the detector, were approximately 0.9% of the velocity of light for the ^{20}Ne-induced reactions and 1.4% for the ^{28}Si-induced reaction. The values, which have an estimated accuracy of ± 2%, were within a few percent of those calculated from the reaction kinematics and the mean energy loss[3]) of the recoiling nuclei in the targets. In each case several independent determinations of the velocity were made.

To measure the feeding times it is also necessary to determine the zero point of the apparatus. By the zero point we mean that position of the plunger when it exactly touches the target and produces only an unshifted peak. This position cannot be realized in practice because of mechanical imperfections in the target and plunger assembly. In the previous measurements[2]) on feeding times with (^{40}Ar,4n) reactions, the recoil velocities were approximately twice as large as those obtained here, and a mechanical estimate of the zero point was adequate. This method is not so satisfactory in the present case where the feeding time, being of the order of 10 ps, corresponds to a micrometer movement of only about 0.03 mm. So we obtained the zero point by measurements on the strong γ-rays arising from Coulomb (and/or nuclear) excitation of rotational states of the target nuclei. In contrast to the states populated in (HI,xn) reactions, these states are populated essentially instantaneously (not quite true since there is a small amount of feeding from the next higher state). Hence, if one extrapolates the curves of log f vs. distance back to unity for these Coulomb excited lines, one should obtain the zero point. Care has to be taken in the extrapolation because the recoiling Coulomb-excited nuclei are not tightly collimated in direction nor do they have constant energy, as in (HI,xn) reactions. Because of this, some of the nuclei will be stopped in the target, and the shifted peak will be very broad due to the wide variation of projected velocity along the beam direction. On the other hand, the maximum shift (recoil velocity) is larger than in a (HI,xn) reaction. It is not possible to calculate precisely either the Doppler-shifted line shape or the form of the log f vs. distance curve. This is because of uncertainties in the angular distributions of the inelastically-excited nuclei and, more importantly, in the energy loss, straggling, and multiple scattering of the ions in the target material. However, a schematic calculation shows that, if one extrapolates linearly back to zero, the accuracy of the zero point is limited in our case by the accuracy of the data points, rather than by lack of knowledge of the form of the curve, provided that one has a number of data points in the region from f = 0.5 to unity. If there were only a small range of recoil velocities, the curve would be linear over a large range of f, but, because of the very large range of velocities in this case, the curve is concave upwards. For values of f near unity, corresponding to small plunger distances, most of the shifted peak arises from low velocity ions. At larger plunger distances the relative contribution of the faster ions increases.

3. Results

Gamma-spectra from the three (^{20}Ne,4n) reactions and from the ^{28}(Si,4n) reaction were first studied at a number of bombarding energies in order to find the best ones for the measurements. The energies chosen were 93 MeV for the $^{150}Sm(^{20}Ne,4n)^{166}Hf$ reaction, 86 MeV for the $^{152,154}Sm(^{20}Ne,4n)^{168,170}Hf$ reactions and 104 MeV for the $^{154}Sm(^{28}Si,4n)^{178}Os$ reaction. In fig. 3 we show examples of the γ-ray spectra from the $^{154}Sm(^{20}Ne,4n)^{168}Hf$ reaction for various plunger settings.

For each transition of interest the intensities of the shifted and unshifted peaks were determined. The most important source of error in this procedure is the estimation of the background under each peak since, apart from the main γ-ray lines, numerous weak ones also occur in the spectra from (HI,xn) reactions. These lines are likely to be associated with different lifetimes than those of the lines of interest and hence can cause uncertainties when they are close together. In some cases account had to be taken of such close-lying lines. After such corrections had been made, the unshifted fraction, f, was calculated. In the ^{20}Ne-induced reactions with the 1 mg/cm^2 targets, f would tend to a finite constant value for large plunger distances even if there were no slow-feeding component, because some ions are completely stopped in the target (fig. 2). In the example of plots of log f vs. target-plunger separation shown in fig. 4, the effect of this constant background, which could also arise from a slow-feeding component, has been removed. The zero-point micrometer setting, determined from the Coulomb-excitation peaks, is also shown in the figure. A similar plot for a 0.5 mg/cm^2 target is shown in fig. 5. In this case the constant background has not been subtracted, and the points for target-plunger separations corresponding to flight times much greater than the lifetime give a direct measure of the amount of slow feeding.

A number of other corrections have to be considered. The energy dependence of the Ge(Li) detector efficiency decreases the apparent intensity of the shifted peak, while the larger effective solid angle of the γ-rays emitted in flight has the opposite effect. In our case the correction from these two opposing effects is much less than the errors of measurement, as is also the correction due to the movement of the plunger varying the effective distance from the detector. Another possible correction is due to the de-orientation effect arising from the large ($\sim$ 27 Mg) magnetic field from the unpaired electrons in the partially stripped ions. As Nordhagen et al.[6]) have shown, this effect is of negligible importance for the decay of the higher spin states from which we derive the feeding times.

The results of these measurements are summarized in Table 1. As before[2]), the mean feeding time, T_f, was taken to be the time required for the unshifted fraction of the fastest observed transition to decrease to 1/e. Clearly this procedure gives an upper limit to T_f, but since the mean lives of the fastest transitions are in all cases estimated to be less than $\sim$ 2 ps, the correction is less than experimental error. As the intensities in Table 1 show, there is a significant amount of side feeding of the states. This is in contrast to the (^{40}Ar,4n) reactions where feeding occurs mainly near the top of the observed band. One expects more side feeding with ligher projectiles, as less angular momentum is brought into the compound system. Since the times associated with the side feeding are not known, we did not attempt to obtain lifetimes for the quasi-rotational states populated in these reactions.

The unshifted fractions for times long compared to the lifetimes, f_{ℓ}, are in many cases likely to be upper limits rather than actual values for the fraction of long-lived feeding component. This is because the many small peaks in the γ-spectra make it difficult to be certain whether one is actually observing a small unshifted peak from the γ-ray of interest or a weak peak from another γ-ray. That these are in some cases upper limits can be seen from Table 1, since a long-lived component feeding one of the upper states must appear in the lower states also.

4. Conclusion

The results in Table 1 show the same general features as the earlier measurements[2]), i.e., feeding times of the order of 10 ps, a tendency for them to increase as the nuclei become more vibrational, and a small ($\lesssim$ 5%) fraction of the population with long feeding time. In this regard ^{178}Os is most nearly comparable with ^{166}Hf as the ratio, $E_\gamma(I)/E_\gamma(4)$, of the γ-ray energies from states of spin I → I - 2 to those from spin 4, show (Table 1). In addition, Kutschera *et al.*[7]) have recently reported similar conclusions in measurements on the nuclei ^{120,122}Xe formed in the ^{108,110}Pd(^{16}O,4n)^{120,122}Xe reactions. The fact that there are now nine cases showing these features considerably strengthens the suggestion that this may be a general phenomenon, at least in rotational and vibrational nuclei.

Any detailed model for the (HI,xnγ) reactions must explain the fast transitions in the yrast cascade as well as the fast transfer from the yrast region to the gsb. Such a model must also be able to explain the phenomenon of "backbending"[8-11]), recently discovered in the rotational bands of a number of nuclei, since the two questions are probably related. At present there is dispute as to whether the backbending is evidence for a complete breakdown of pairing (Mottelson-Valatin effect)[12-14]) or for a breaking of just one pair in a high-j orbital[15]). The resolution of this problem is of great interest. So far the most detailed quantitative calculations on the backbending and the feeding have been made by Stephens and Simon[15]), who considered the latter possibility.

Acknowledgments

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Table 1. Summary of data. Symbols we defined in the text.

Nucleus	Velocity (%v/c)	T_f (ps)	I	$E_\gamma(I)$	$E_\gamma(I)/E_\gamma(4)$	f_ℓ (%)	Relative Intensity
^{166}Hf	0.96 ± 0.002		4	311.8	1.000		1.41
			6	426.5	1.368	3 ± 3	1.00
			8	∿511	∿ 1.64		
			10	565.0	1.812	10 ± 3	0.55
		11 ± 3	12	593.9	1.905	5 ± 4	0.41
^{168}Hf	0.91 ± 0.02		4	261.5	1.000		1.22
			6	371.1	1.419	13 ± 1	1.00
			8	456.5	1.746	5 ± 3	0.88
		5 ± 2.5	10	522.0	1.996	1.5 ± 1.6	0.72
			12	∿569	∿ 2.18		0.54
^{170}Hf	0.89 ± 0.02		4	221.0	1.000		1.35
			6	320.9	1.452		1.00
			8	400.5	1.812	2 ± 2	0.78
			10	462.3	2.092	7 ± 4	0.65
			12	∿511	∿ 2.31		
		3 ± 3	14	550.8	2.492	8 ± 5	0.32
^{178}Os	1.39 ± 0.02		4	266.8	1.000		1.16
			6	363.0	1.361		1.00
			8	432.6	1.621	1 ± 2	0.86
			10	488.3	1.830	6 ± 3	0.56
		$12 \pm ^{2.5}_{4}$	12	538.0	2.016	6 ± 4	0.47

Figure Captions

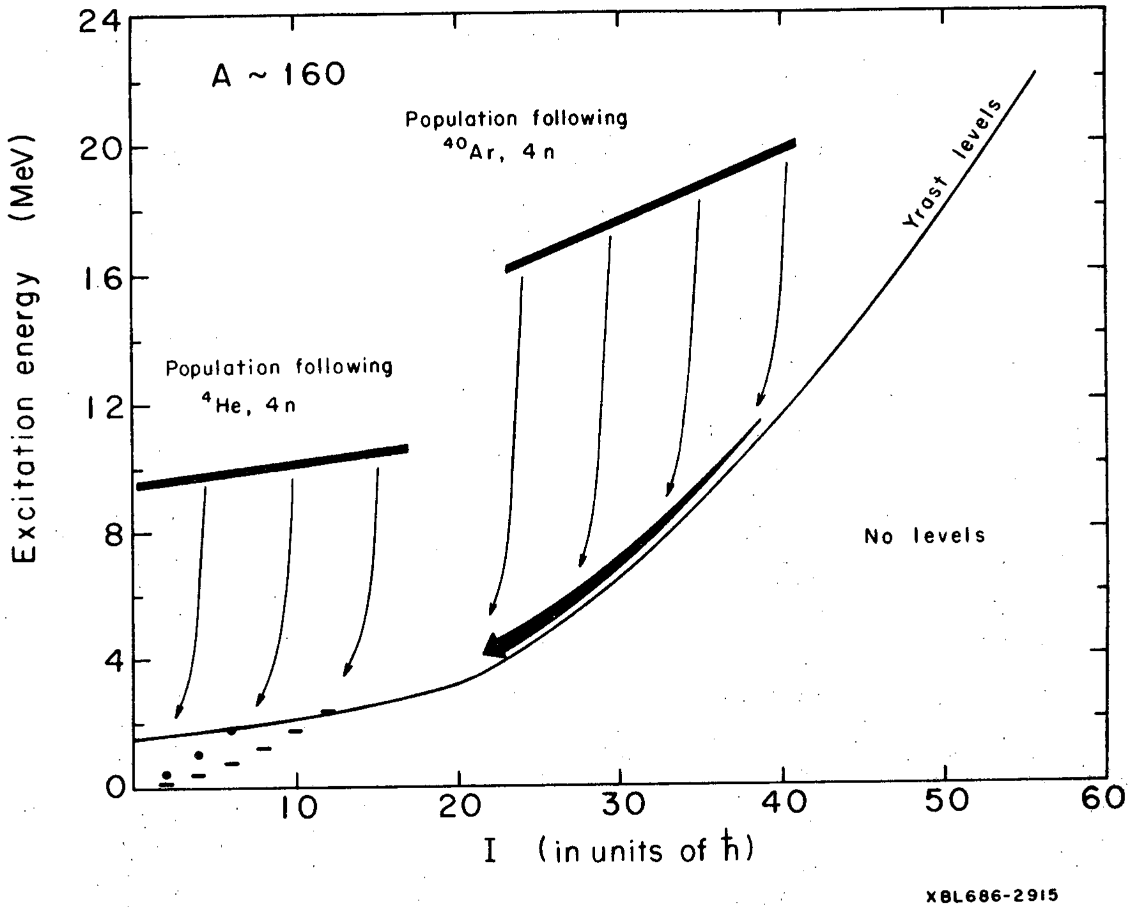
Fig. 1. Schematic figure showing the energy levels in a nucleus of mass ≈ 160 versus angular momentum. Indicated on the figure are (i) the lowest non-g.s.b. energy levels for each spin (yrast levels), (ii) the regions of populated states following (He,4n) and (Ar,4n) reactions, and (iii) the g.s.b. levels of a typical vibrator (dots) and rotor (dashes). (From ref. 1.)

Fig. 2. Line shapes for the $10^+ \rightarrow 8^+$ transition in ^{168}Hf obtained with 1 mg/cm^2 and 0.5 mg/cm^2 targets. The continuous backgrounds under the peaks have been subtracted. In each case the upper curve (dots) shows the line shape for a large plunger distance, corresponding to an average flight time much greater than the lifetime of the 10^+ state. The lower curve (open circles) shows the line shape for a smaller plunger distance where some of the excited nuclei would be expected to decay in the plunger and give an unshifted peak. The continuous lines are only to guide the eye. The dashed line indicates the expected shape of the upper curve for the 1 mg/cm^2 target, if there were no straggling.

Fig. 3. Pulse height spectra for the γ-rays from the ^{152}Sm(^{20}Ne,4n)^{168}Hf reaction for various plunger settings.

Fig. 4. Unshifted fraction, f, as a function of micrometer setting and flight time for transitions following the ^{152}Sm(^{20}Ne,4n)^{168}Hf reaction with a 1 mg/cm^2 target. The approximately constant value of f for large micrometer settings has been subtracted from all values of f. The horizontal error bar indicates the experimental error in the zero of the time scale.

Fig. 5. Unshifted fraction, f, as a function of micrometer setting and flight time for transitions following the $^{152}Sm(^{20}Ne,4n)^{168}Hf$ reaction with a 0.5 mg/cm^2 target. In some cases the points have been slightly displaced horizontally for clarity of presentation. The values of f_ℓ, the long-lived unshifted fraction, in Table 1 are obtained by averaging the points in this figure for flight time greater than those where the corresponding curve in fig. 4 has dropped to 1% (dashed lines).



A ~ 160
Population following
^{40}Ar, 4n
Population following
^{4}He, 4n
Yrast levels
No levels
Excitation energy (MeV)
I (in units of ħ)
XBL686-2915

Fig. 1

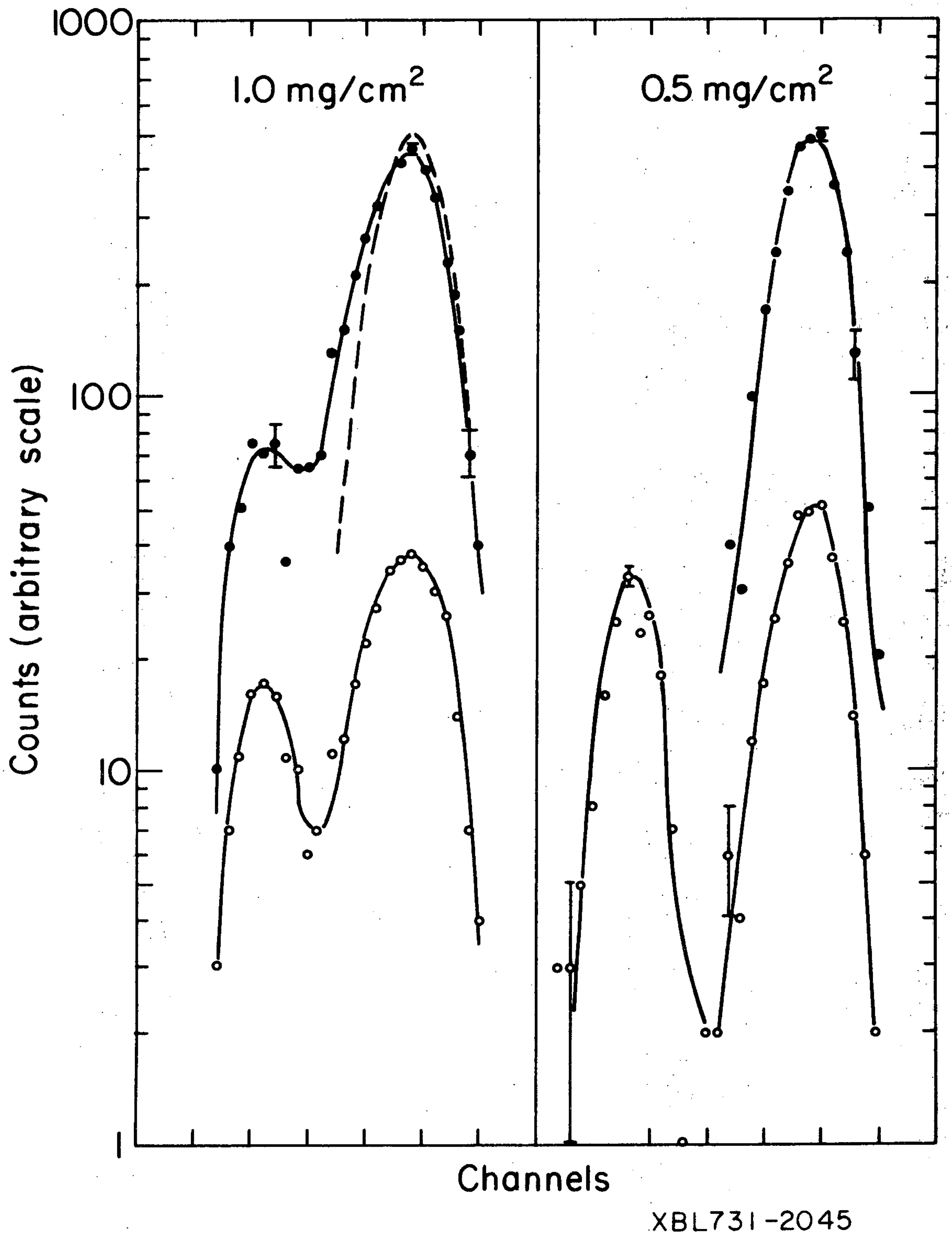

1000
100
10
1
Counts (arbitrary scale)
1.0 mg/cm²
0.5 mg/cm²
Channels
XBL731-2045

Fig. 2

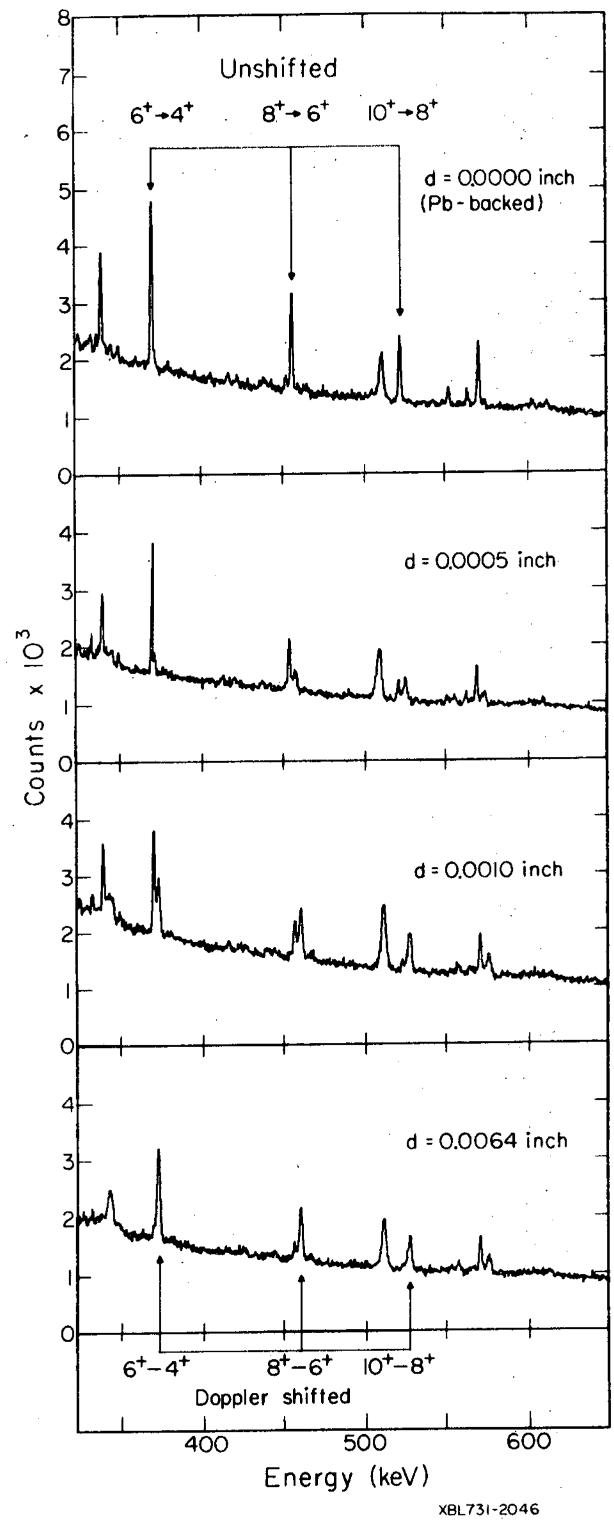

Unshifted
6+→4+
8+→6+
10+→8+
d = 0.0000 inch
(Pb-backed)
d = 0.0005 inch
d = 0.0010 inch
d = 0.0064 inch
6+–4+
8+–6+
10+–8+
Doppler shifted
Counts x 10^3
Energy (keV)
400
500
600
XBL731-2046

Fig. 3

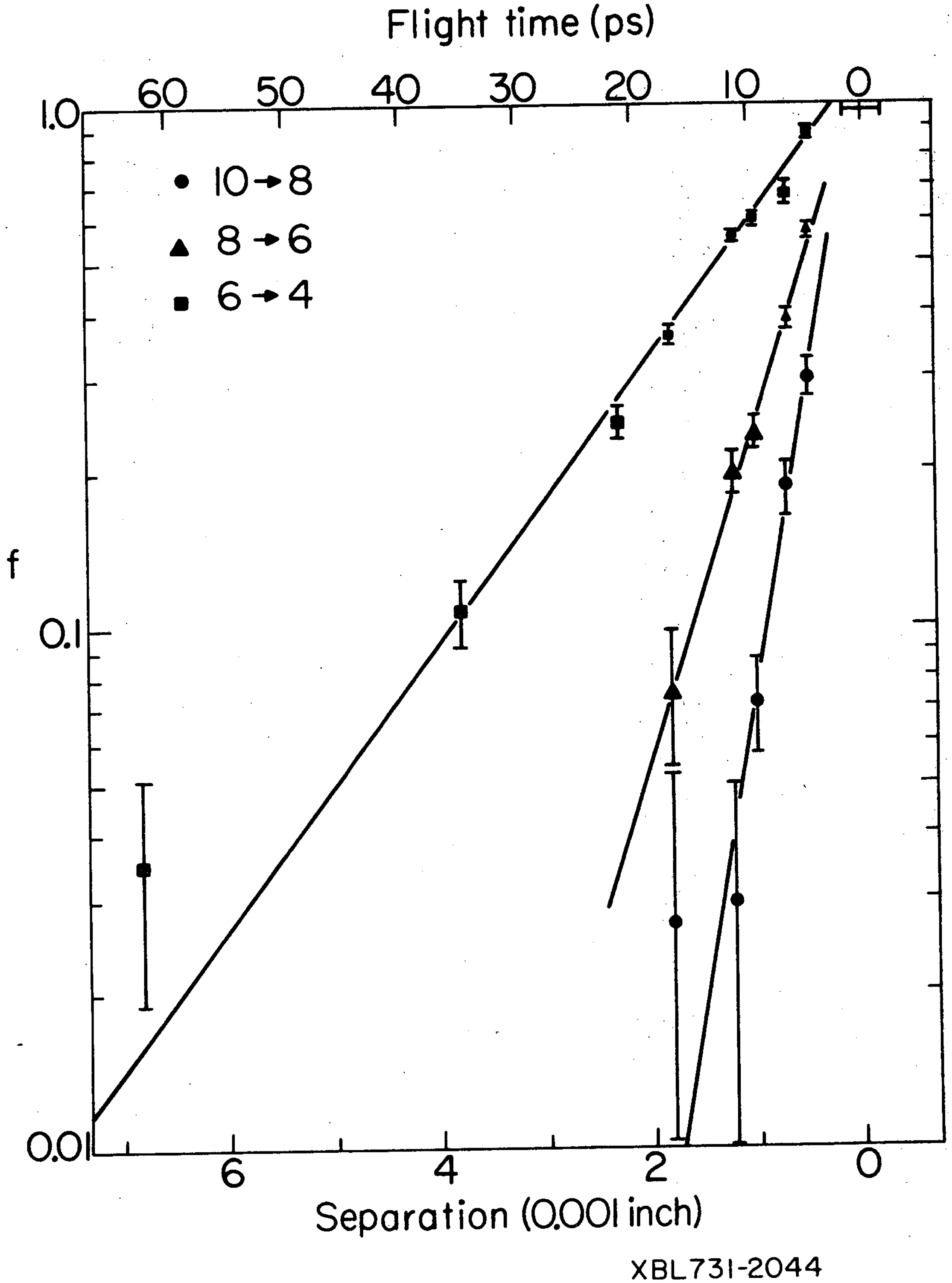

Flight time (ps)
60
50
40
30
20
10
0
1.0
0.1
0.01
f
10→8
8→6
6→4
6
4
2
0
Separation (0.001 inch)
XBL731-2044

Fig. 4

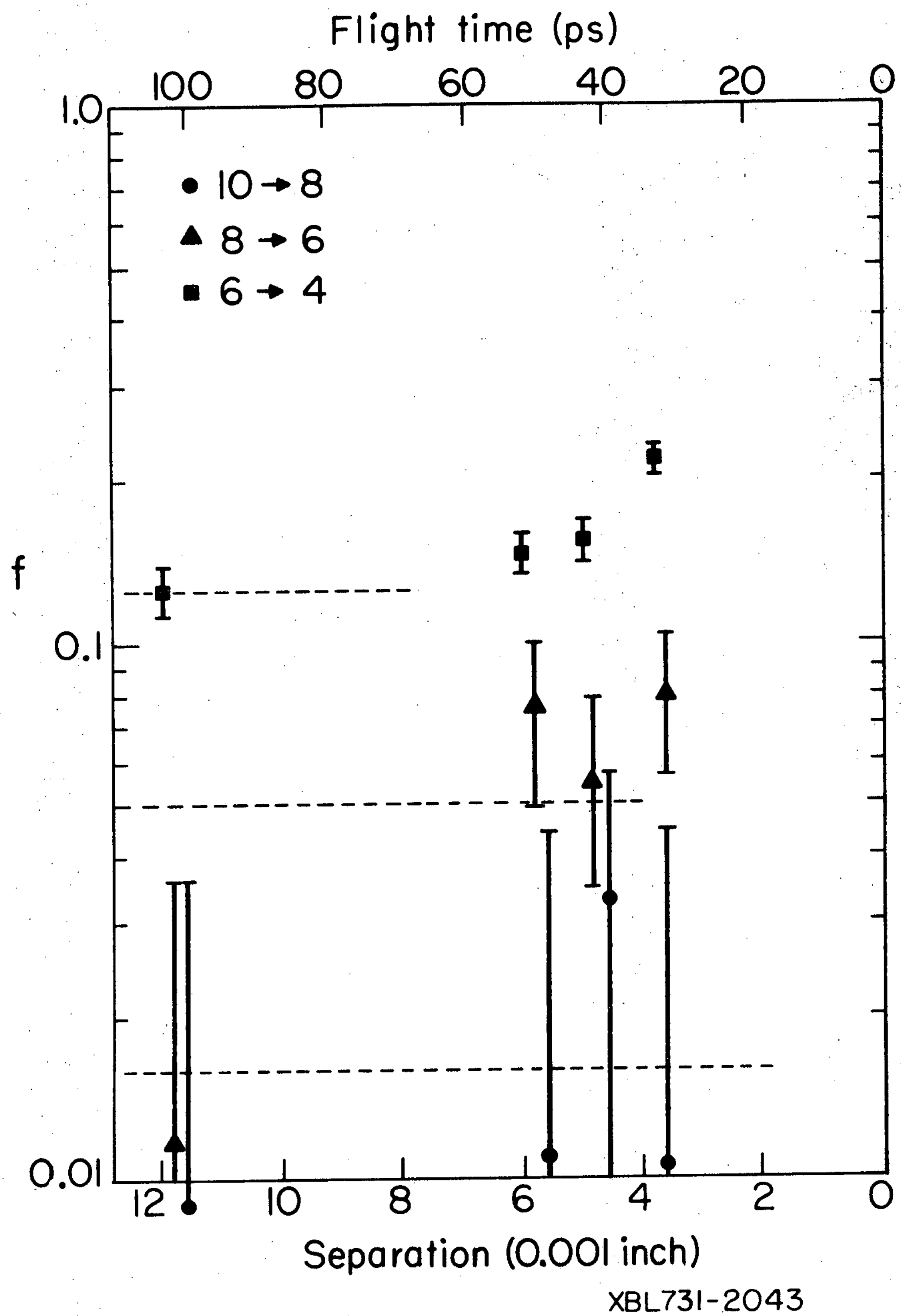

Flight time (ps)
100
80
60
40
20
0
1.0
0.1
0.01
f
10 → 8
8 → 6
6 → 4
12
10
8
6
4
2
0
Separation (0.001 inch)
XBL731-2043

Fig. 5

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